

Evaluating the spatial and temporal dynamics of farm and field phosphorus and potassium balances on a mixed crop and livestock farm

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Abstract

Methods to track P and K on farms over time at varying spatial scales can improve farm agronomic and environmental performance monitoring. An annual nutrient balance was used to determine P and K balances at varying spatial scales on a 128 ha mixed crop and dairy farm in a central Pennsylvania limestone valley for each of nine years. Alfalfa (*Medicago sativa* L.) and corn (*Zea mays* L.) occupied 60% and 40% of the cropland, respectively. Inputs of P and K to the farm exceeded outputs over the study period. Net increases of P and a decrease in K were determined in the aggregate of all fields over the 9-yr period. The balance of P and K varied with time within a field, and by field within a year because nutrient inputs and removals varied with crop selection, management tactics, and year in the rotation. Recognizing that increases in field P are in proportion to P entering the farm can help reduce P accumulation in fields by addressing surpluses at their source or balancing managed flows for the farm. Conversely, decreases in field K associated with forage crops may be the reason for additional supplemental K inputs to the farm. Monitoring nutrient stocks (soil testing) and flows (input/output balances) at different scales in conjunction with spatial patterns of nutrient balances can be the foundation for integrating farm activities and information technologies in a new generation of performance enhancing tools.

Introduction

Despite our understanding of P and K build-up and supply to crops, high to excessive P and K concentrations in soils occur frequently on many mixed crop and livestock farms in Pennsylvania (Young et al. 1985; Bacon et al. 1990). Since each management decision on a farm influences some other aspect of the farm, management of P and K stocks in crop fields on these mixed farms becomes more difficult as the number of farm management decisions increases. Selecting crop rotations, feed rations, animal stocking density in relation to feed production, and adhering to soil test recommendations are all influenced by other strategic decisions that can affect nutrient bal-

ances, crop production, and nutrient loss to the environment (Westphal et al. 1989).

Farm-scale studies have shown that the balance of P and K is greater on farms with high animal stocking densities, especially non-ruminant farms, than those with lower densities (Adams and McAllister 1975; Granstedt 1995). Adams and McAllister (1975) suggested that as animal stocking densities increased, the need for purchased fertilizers decreased because the stock of nutrients in manure was more than sufficient to supply crops with the needed nutrients. Survey data on the economic return to farms that rely more heavily on purchased feeds indicate that these farms have the highest return to the farm (Hastings 1995). However, limiting soil test levels can restrict the economic performance of a farm that depends on

income from animal enterprises (Westphal et al. 1989) or a related sector (Komen and Peerlings 1998).

The build-up and draw down of soil P and K stocks at the field and farm scale can be studied using balance sheets. For example, balance sheet methods were used to study the flow and build up of P and K at the field scale on dairy farms (Bacon et al. 1990). Annual P and K balances on this mixed livestock farm varied spatially. Balances were not the same in adjacent fields, and balances among corn crops or alfalfa crops were different. Randall et al. (1997) measured decreases in soil P and K from high to optimum ranges after five years of cropping. Mapping annual field nutrient balances can complement temporal balances by locating specific sites (fields) of nutrient accumulation or depletion that can be the basis for the next iteration in nutrient management.

In this study, farm and field balances were used to assess potential management concerns associated with a typical mixed crop and livestock farm in a Pennsylvania limestone valley. Additionally, field balances were mapped to visually identify fields that do not meet nutrient management goals better than simple balances.

Materials and methods

The study was conducted on a mixed crop-livestock farm in Centre County, Pennsylvania between 1986 and 1994 (Saporito and Lanyon 1998). Farm soils associations are the Hagerstown-Opequeon-Hublersburg and the Murrill which were formed in limestone residuum and colluvium respectively (USDA 1981). Both soil associations can be characterized as shallow or deep, well-drained soils overlying limestone bedrock. The soils on the farm are well suited to row crop and hay production.

The farm included an 95 cow Holstein (*Bos taurus*) herd with an average of 65 lactating cows, 15 heifers and 15 dry cows. The herd size was maintained throughout the study. Average annual milk production was 544 Mg. The farm operation included a small Angus cow-calf herd with a few steers fattened each year. Average managed cropland used in the study was 113 ha including rented acres. Additionally 15 ha of the farm was utilized for pasture and barnyards.

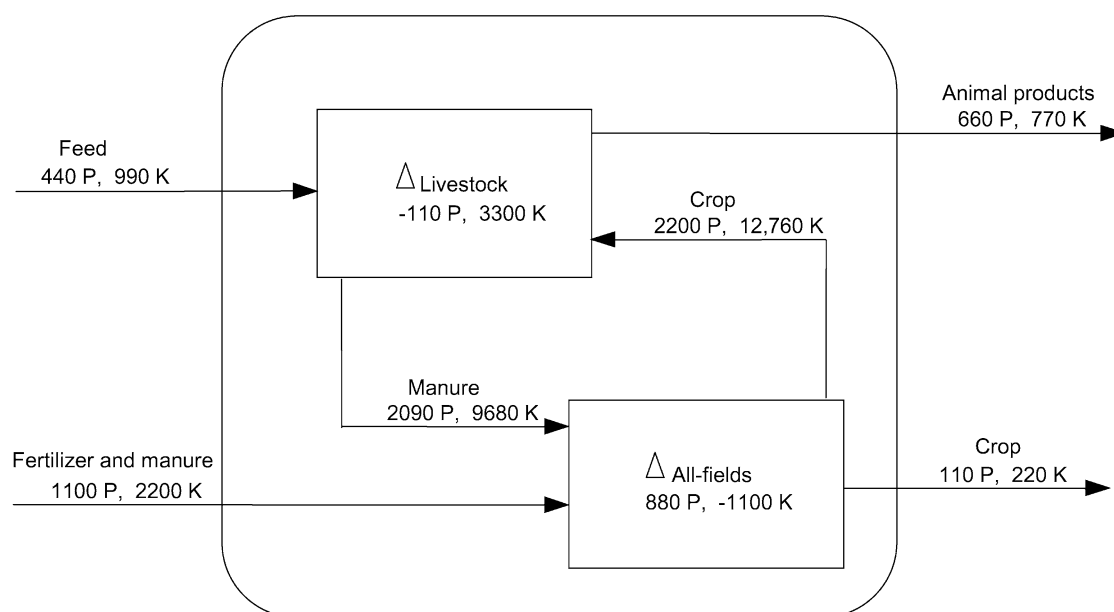
Field crop production included corn (*Zea mays* L.) for grain and silage, and alfalfa (*Medicago sativa* L.),

alfalfa-timothy (*Phleum pratense*) and Reed canarygrass (*Phalaris arundinacea* L.) harvested as haylage or hay. A generalized rotation for the fields consisted of two or three years of corn followed by three or four years of forage. Approximately 60% of the farm area was in an hay or haylage crop while the remaining 40% of the land was planted to corn. In 1994 green beans (*Phaseolus vulgaris* L.) were grown on 10 ha. Harvested haylage, corn grain, and corn silage usually were stored in one of five oxygen-limited silos and fed to livestock. Forage crops were occasionally harvested as dry hay. Green beans were grown and sold under contract with a local cannery. The average yield for corn grain and forage crops was 6.9 and 7.3 Mg ha⁻¹ yr⁻¹, respectively.

Crop production details have been described previously (Saporito and Lanyon 1998). Corn planted following alfalfa or alfalfa-timothy received only 112 kg ha⁻¹ starter fertilizer (8-24-8, N-P-K) at planting. Corn planted following corn received about 145 Mg ha⁻¹ (wet weight) of dairy slurry before planting (2.63, 0.53 and 1.98 kg Mg⁻¹ N, P and K, respectively) and the same starter fertilizer. Alfalfa and alfalfa-timothy hay were generally established in the spring after corn with dairy slurry applied before planting at the rate of about 100 Mg ha⁻¹. Additional manure applications averaging 50 Mg ha⁻¹ yr⁻¹ and additions of KCl were made in succeeding years. Slurry was spread mostly in the months of April and May on fields to be planted to corn, and October and November to alfalfa fields. Some additional bedded pack of sawdust and dairy manure (17.5, 8.7 and 16.0 kg Mg⁻¹ N, P and K, respectively) and a bedded pack with steer manure (3.90, 1.79 and 4.66 kg Mg⁻¹ N, P and K, respectively) were spread periodically on pasture or crop fields located closest to the barns. Hog manure (3.19, 0.66 and 3.52 kg Mg⁻¹ N, P and K, respectively) from a neighboring operation was spread periodically on a few corn fields.

Data for this research were obtained from nine years of records (1986–1994) using a record keeping system developed by Lanyon and Meij (1989). The records included the date, weight, moisture, origin and destination of all materials moving to, from, and within the farm. All forage and corn harvests, and periodic manure spreader loads were weighed with a 22.7 Mg capacity scale immediately prior to storage or field application.

Grab samples of all materials at time of application (for manures) and harvest (for all crops) were collected by research staff or the farmer and stored in



Δ Livestock = change in the livestock component; Δ All-Fields = change in All-fields component.

Figure 1. Annual average P and K flow to, within, and from the study farm (kg yr⁻¹).

plastic bags or liter containers so that moisture and nutrient (P, K) concentrations could be determined. Moisture concentrations were determined by drying in a forced air oven at 70 °C until weight loss ceased. Analysis of P and K was done by the methods of Dahlquist and Knoll (1978). Manure nutrient concentrations were determined by methods of Doty et al. (1982).

Phosphorus and K balances for each of the managed fields, the set of all-fields, the livestock facilities, and the farm were determined by subtracting nutrient outputs from inputs in the managed flows at the specified farm boundaries (Lanyon and Schlauder 1987). The balance for the all-fields component was determined by subtracting the sum of outputs from all fields from the sum of inputs to all fields. Inputs to the livestock compartment included harvested crops, purchased feed, minerals, and bedding. Livestock component outputs included all milk and animals sold, and manure exports. Farm balance equalled the difference between all the nutrients moving onto the farm minus the nutrients leaving the farm in the managed flows.

Soil samples (0 to 20 cm) were taken on an annual basis for each field in late summer through fall by a

crop consulting service. Bray P1-P (Olsen and Sommers 1982) was determined for 1986 to 1992 and Mehlich-3 P (Mehlich 1984) for 1993 and 1994. Soil K was extracted with ammonium acetate (Knudsen et al. 1982) between 1986 and 1992 and with Mehlich-3 for 1993 and 1994.

Base maps of both the soil mapping units and the farm field boundaries were created using a raster geographic information system on a microcomputer (Saporito and Lanyon 1998). Each P and K map was classified into 15 and 50 kg ha⁻¹ classes, respectively (Think Space 1992).

Results and discussion

Farm – phosphorus

Total farm P inputs (1540 kg yr⁻¹) were about twice the outputs (770 kg yr⁻¹; Figure 1), resulting in an average annual total farm gate surplus of 770 kg yr⁻¹. Farm P inputs from starter fertilizer, hog manure, dairy mineral supplements, and feed were more variable (SD: ± 1102 kg yr⁻¹) than farm outputs (SD: ± 128 kg yr⁻¹) from milk, animals, and crops. Be-

Table 1. Phosphorus and potassium balances for the managed flows to and from all crop fields.

	1986	1987	1988	1989	1990	1991	1992	1993	1994	Avg.
Phosphorus balance (kg ha ⁻¹)										
Corn	11	14	24	24	32	45	26	22	8	23
Hay	-6	-4	-3	3	3	9	3	7	-1	1
All	-2	2	6	10	11	22	10	11	1	8
Potassium balance (kg ha ⁻¹)										
Corn	50	30	74	145	111	118	76	121	41	85
Hay	-109	-23	-54	-14	-66	-21	-138	-32	-111	-63
All	-47	-2	-10	50	-11	30	-63	20	-51	-9

cause this farm has a relatively low animal density (0.69 au ha⁻¹; 1 au is 454 kg) it is expected that farm gate balances would not exceed inputs due to a low necessity for purchased feeds (Granstedt 1995; Nguyen et al. 1995; Haygarth et al. 1998). Inputs of P in feed to this farm remained low throughout the study relative to P inputs from fertilizer and manure, suggesting that much of the farm gate surplus is due to additions of nutrients directly to farm fields.

Farm – potassium

Farm K inputs exceeded K outputs by 2100 kg yr⁻¹ (Figure 1). The flow of K to the farm came from purchased fertilizer, feed, and hog manure at 1650, 990, and 550 kg yr⁻¹, respectively. There was an apparent surplus of farm K despite a net annual deficit of K in the fields of -1100 kg yr⁻¹ while an annual surplus of 3300 kg K yr⁻¹ was calculated for the livestock compartment on the farm. Bacon et al. (1990) also reported a positive livestock K balance and a negative field K balance, 1772 and -577 kg ha⁻¹ respectively, on a southeastern Pennsylvania dairy farm with 2.5 au ha⁻¹. Although the herd size was similar to the study farm, the land area was smaller (41.2 ha) and feed purchases were greater.

The surplus of K in the livestock facility of both farms may be due to one or more sources of sampling errors in developing the budgets (Bacon et al. 1990). Analytical nutrient quantification errors within the livestock component are more likely to occur in manures than they are in crops, milk and fertilizers (Oenema and Heinen 1999). An examination of the nutrient budgets used in this study suggests that an accumulation of K in exercise areas and pastures may be occurring, but is unknown because nutrient movement within the livestock component was not measured. Additionally, it is possible that the K in

milk from the study farm is greater than the standard reference value used in the nutrient budget worksheets (Lanyon and Schlauder 1987).

All fields – phosphorus

The annual average P balance for all farm fields including rented cropland was 8 kg ha⁻¹ yr⁻¹ (Table 1). Annual P balance ranged from -1 to 23 kg ha⁻¹ during the study period. Phosphorus balance was lowest in 1986 when a larger than normal acreage of corn was harvested as silage due to dry weather conditions. The highest P balance occurred in 1991, a year in which P outputs were reduced due to lower than normal yields associated with dry weather during the growing season.

The average annual P balance for corn and hay fields was positive while the soil P balance was greater for corn fields than hay fields (25 kg ha⁻¹ versus 1 kg ha⁻¹, respectively). Because removals of P in corn and hay were similar (23 and 19 kg ha⁻¹, respectively), the difference in balance for the two crops depended on nutrient application rates. Phosphorus was applied to corn and hay at the rates of 45 and 20 kg ha⁻¹ yr⁻¹, respectively. All P applied to hay crops was from manure, while less than 50% of the P applied to corn was from manure and the remainder from starter fertilizer.

The average annual STP for all fields ranged from 85 to 130 kg ha⁻¹ during the 9-yr period (Figure 2) and was in the optimum range for crop growth seven out of the nine years. Although the average STP was not the same from year-to-year, STP was essentially the same at the end of the study period as it was in the beginning.

Because of the low farm stocking density and limited feed purchases, a low or negative all-field P balance might be expected. However, management

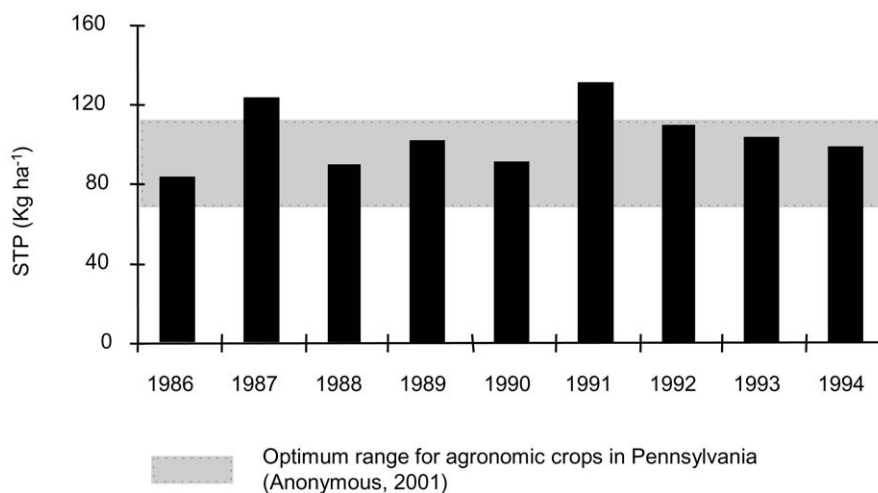


Figure 2. Annual mean available soil test P (STP) for all fields on the study farm.

tactics that include the use of off-farm manure and starter fertilizer led to a small positive P balance for the crop fields on the farm. Minor adjustments in management tactics, such as eliminating starter fertilizer for corn, may be necessary to reduce P pollution potential (Wang et al. 1999) and/or reduce farm costs due to surpluses. In addition, reduction of P to fields in the form of swine manure would be an option to reduce the P loading. However, this would eliminate the opportunity for a neighboring operation to export excess P in the swine manure. Criteria have been suggested in The Netherlands to evaluate farm performance on the basis of potential P loss (Kloen and Vereijken 1995). Ecological acceptability on farms is attained when STP is maintained in the optimum range, and the P input/output ratio is 1:1. Further, if STP is greater than the optimum range for crop growth, the P input to output ratio must be less than 0.5 to achieve ecological acceptability. Because the average STP for all fields on the study farm was never less than optimum (Figure 2) and the P input/output ratio was > 1.0 for eight out of nine years, the study farm fails to meet the ecological acceptability criterion of The Netherlands in eight out of nine years. In the United States a P-index incorporating STP and P application management along with soil and hydrologic features to assess P loss potential has been developed (Sharpley 2000) and may provide some management information in addition to simple balance criteria.

Accumulations of P may occur on farms with high animal stocking densities due to greater feed purchases than on farms with lower stocking densities

and smaller feed purchases (Lanyon 1990). A poultry (layers) farm in southeastern PA with an animal density of 36 au ha⁻¹ had an all-fields P balance of 562 kg ha⁻¹ yr⁻¹. A 2.4 au ha⁻¹ hog operation reported annual P surpluses of 25 kg ha⁻¹ (Granstedt 1995).

All fields – potassium

The annual average K balance for all farm fields was -9 kg ha⁻¹ yr⁻¹ (Table 1). The annual K balance ranged from -70 to 50 kg ha⁻¹ during the study period. The most negative K balances occurred in 1992 and 1994, years when inputs were low (74 and 81 kg ha⁻¹) and outputs were large (139 and 126 kg ha⁻¹). There was a difference in all fields balance between crops (Table 1). A net K accumulation of 85 kg ha⁻¹ was measured for corn fields while a K depletion of -63 kg ha⁻¹ was measured for hay fields during the 9-yr period. Both inputs and crop removals can explain the differences in balances. Corn received 122 kg K ha⁻¹, while hay received 93 kg K ha⁻¹. Conversely K removals in harvested corn were much lower than K removal in harvested hay (37 and 156 kg ha⁻¹, respectively).

The average soil test K (STK) for all fields for the farm was greater than the optimum range in all years of the study (Figure 3). However, STK increased with time from 1988 to 1991, and decreased from 1991 to 1994. Both annual average K balance and STK for all fields decreased when comparing 1986 to 1994. If the removals of K continue to be greater than additions, then STK will fall below the optimum range for crops in Pennsylvania (Anonymous 1994). Additional K

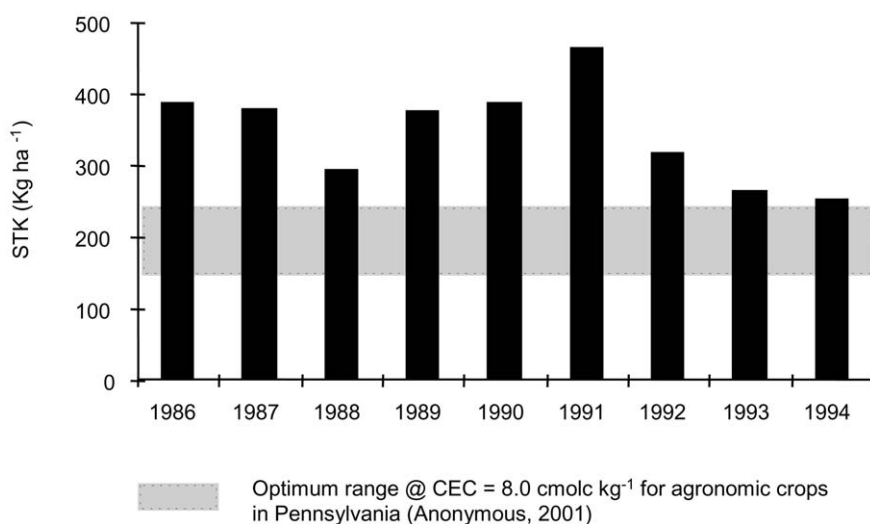


Figure 3. Annual mean available soil test K (STK) for all fields on the study farm.

applications will be required to replenish the soil stock of K within a few years if this management continues.

Soils may supply K for long periods of time even when there are net K removals (Kaffka and Koepf 1989). A 52.4 ha German dairy farm with an animal density of less than 1 au ha⁻¹ had an annual field deficit of 8 kg ha⁻¹ yr⁻¹ for 20 years. Although farm soils tested low to medium in soil K throughout the study, the farm was able to steadily increase milk production without importing large quantities of plant nutrients. Elsewhere, reports from a mixed livestock farm with low animal densities (1.04 au ha⁻¹) indicated that a lack of K mineral fertilizers was leading to decreases in field stocks of K (Nolte and Werner 1994).

Phosphorus and potassium management performance

Farm agronomic and/or environmental performance may be evaluated using two criteria: (1) nutrient input/output ratios (a measure of nutrient flows); and (2) levels of available soil nutrients (a measure of soil stocks). The first set of conditions is based on three different input/output ratios. These ratios are: inputs < outputs; inputs = outputs; and inputs > outputs. Second, soil testing may be used to determine the nutrient status of fields. Generally soil tests report nutrient status as below optimum, optimum, and above optimum (Anonymous 2001). The two criteria can be arranged to identify different farm performance sce-

narios (Figure 4). For example, if STP is above optimum, then field management resulting in P outputs greater than P inputs is preferred. In contrast, if STP is low, then nutrient flows should be managed so that P inputs are greater than P outputs to improve agronomic performance.

When available soil nutrients (P and/or K) are optimum and nutrient inputs are equal to outputs, then yields will not be limited by these nutrients (Figure 4). Equal could mean that managed P and K are within some reasonable range such as ± 10 kg ha⁻¹ for P and ± 25 kg ha⁻¹ for K. Further, the risk of P loss to the environment generally will be low. Potential farm environmental performance may be poor when STP is above optimum and nutrient inputs exceed outputs. Additionally, excessive K stocks can affect animal performance. For example, non-lactating dairy cows may be more susceptible to milk fever when fed forages produced on high-K soils that contribute to rations containing 3% or more K than when fed lower K rations (Horst and Groff 1997). Conversely, agronomic performance is likely to suffer when STP and/or STK are low and nutrient inputs are less than outputs.

The weighted average STP for all fields on the study farm was in the optimum range seven out of nine years and above optimum for two (1987 and 1991; Figure 2). Soil P balance (for all fields) is within ± 15 kg ha⁻¹ yr⁻¹ for all years, indicating that P stocks should be maintained with these flows (Figure 2). Accepting a management accuracy range of ± 15 kg ha⁻¹ for P would indicate that P man-

Annual Input-Output Status			
Soil Test Level	-	0	+**
below optimum	Agronomic liability		Preferred
optimum	OK*	Ideal	OK*
above optimum	Preferred	OK	Potential environmental and/or biological liability

* long-term performance can cause an undesirable change in the soil test level

** extreme balances can create environmental or biological problems, especially when the nutrients are supplied in manure

Figure 4. A soil test and nutrient balance matrix to assess farm agronomic and/or environmental performance.

agement performance on the farm is 'ideal' seven out of nine years and is OK (satisfactory) for two years (Figure 4).

Available soil K exceeded the optimum range in all years of the study (Figure 3). Potassium inputs were within $\pm 50 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (for all fields) for all years except 1992. The combination of soil test and K balance suggests that, although STK remained above optimum levels for crop growth, it is declining. In the short term (1 to 5 years), current management tactics in which K outputs exceed inputs are acceptable. However, as removals of K continue to exceed inputs and K stocks in fields continue to decrease, periodic soil testing will be required so that K stocks are not depleted below the agronomic response threshold. In the long term (5 to 10 years), it is likely that the stock of K will decrease and additions of mineral K fertilizer will need to be added to the stock of on-farm manure to adequately supply K needs to crops (Nolte and Werner 1994).

Spatial patterns of balances

Nutrient balance in a field was generally independent of the nutrient balance in adjacent fields, and the pattern created by field level balances was heterogeneous, as illustrated for 1991 (Figures 5 and 6). Fields

planted with corn were most commonly associated with positive P and K balances (input > output). While the balances for the majority of hay fields were negative for both nutrients, some hay fields balances were positive. The spatial pattern reflected the management tactics and performance for each field as well as the pattern of field allocation to each of the major crops. The management of each field changed during the study period so that the spatial patterns of balances varied with time.

Mapping balances may be useful to farmers because it will assist them in locating fields with extreme balances (Meij et al. 1992). Maps of the nutrient balances may help farm operators identify fields that do not meet targeted nutrient management goals more easily than tabulated data. For example, field B11 in 1991 (Figure 5) has a pattern identifying it as a field with a P balance greater than 50 kg ha^{-1} and a K balance in excess of 250 kg ha^{-1} . The map is a visual aid that can also be used to relate hydrologically active areas (Gburek et al. 2000) to fields where P stocks are increasing and subject to P loss.

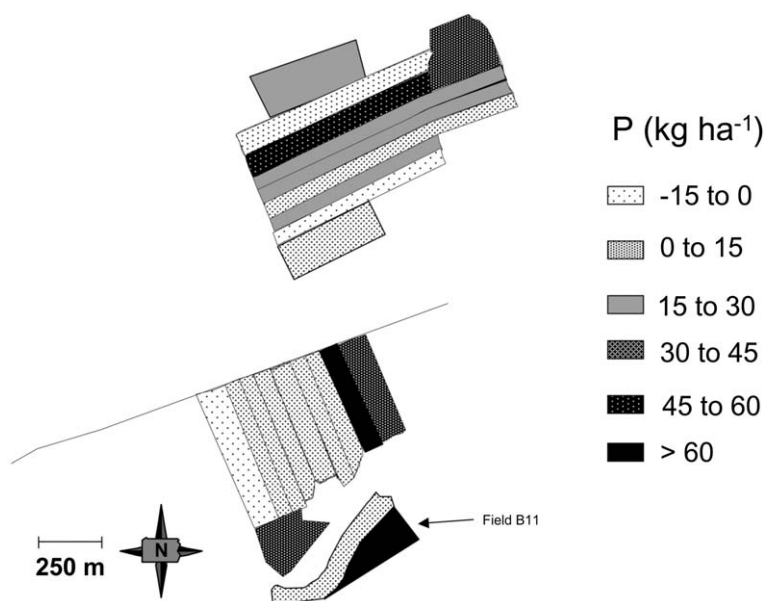


Figure 5. Spatial pattern of field P balances in 1991 at the study farm.

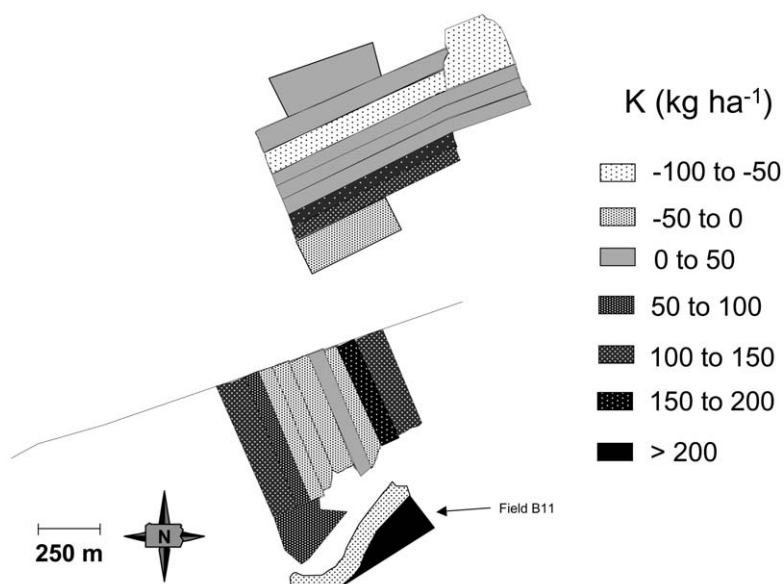


Figure 6. Spatial pattern of field K balances in 1991 at the study farm.

Conclusions

Monitoring nutrient balances at both the field and at the farm gate proved to be a successful way of uncovering farm management concerns not obvious by determining nutrient balances at the farm gate alone. While the P stock for all fields increased by an average 8 kg ha⁻¹ yr⁻¹ during the 9-yr period at the farm

gate, individual field P additions were as much as 100 kg ha⁻¹ greater than removals in any year for some fields. Phosphorus surpluses increased in fields where corn was grown more frequently than hay. These changes in the P stock were closely associated with the farmer strategy to use on-farm manure as a primary source of N for corn production. Surplus P at the farm gate could largely be eliminated by reducing

starter fertilizer purchases and the amount of hog manure accepted from a neighboring farm. Although the farm gate K was in surplus, this K was unaccounted for in the livestock component of the farm. Potassium deficits for all fields indicate that current farm management practices are reducing the stock of available K in the fields from above optimum to optimum soil test. Continued depletion of the soil K stocks will affect crop agronomic performance in the future.

Farm nutrient information management can integrate the snapshots of individual soil tests with the year-to-year patterns in farm gate and field nutrient balances for use in nutrient management assessment tools. Farm nutrient management strategy, the tactical allocation of nutrient resources, and the efficacy of day-to-day operations can all be evaluated with adequate multiple-year information. The spatial dimension of farm activities can be represented by nutrient balance thematic farm field maps as another tool to assist producers and crop consultants in the nutrient management process. Additionally, information technology products such as maps of balances could complement efforts for implementation of other management tactics with spatial dimensions, such as the P-index.

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